FRACTURE ZONE TECTONICS, CONTINENTAL MARGIN FRAGMENTATION, AND EMPLACEMENT OF THE KINGS-KAWEAH OPHIOLITE BELT, SOUTHWEST SIERRA NEVADA, CALIFORNIA

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INTRODUCTION

The Sierra Nevada foothill metamorphic belt is a 450 km long assemblage of remnant continent-derived epiclastics, arc volcanics, pelagic-hemipelagic sediments, and ophiolite slices. The various lithologic units range in age from Ordovician to Jurassic. Lithologic units are lenticular at scales ranging up to 150 km and strike about N. 30°W. parallel to the trend of the metamorphic belt (Fig. 1). Many units are penetratively deformed with a variety of near vertical foliation surfaces. The lithologic units are generally bounded by steep dipping fault and melange zones, but locally depositional contacts can be recognized. From at least latitude 38°30'N southward, latest Paleozoic to possibly early Mesozoic disrupted ophiolite occurs as remnant oceanic basement beneath Triassic to Jurassic arc volcanics and interstratified continent-derived epiclastics. Along the northern part of this segment of the metamorphic belt the ophiolitic rocks occur as scattered basement exposures surrounded by the younger volcanic and epiclastic rocks (Morgan and Stern, 1977; Behrman, 1978; Saleeby, unpub. field data). Further south in the Kings-Kaweah terrane deeper structural levels of the foothill metamorphic belt are exposed. Here a nearly continuous 125 km long ophiolite belt occurs with scattered remnants of early Mesozoic arc volcanic and epiclastic rocks depositionally above it. The ophiolite belt is named informally the Kings-Kaweah ophiolite belt after the Kings and Kaweah Rivers which transect it. This ophiolite belt constitutes part of the same oceanic basement terrane that is locally exposed further north amidst the arc volcanics and epiclastics.

The Kings-Kaweah ophiolite belt constitutes a significant segment of the foothill metamorphic belt. Within it exist the only remnants of a complete ophiolite succession to be found throughout the entire Sierran terrane. In addition, since it represents the deepest exposure of foothill metamorphic rocks, it affords the best opportunity to study the tectonic and petrogenetic history of the oceanic basement terrane upon which Mesozoic continental margin rocks were deposited. The purpose of this paper is to: 1) give a general description of the ophiolite belt; 2) expand upon critical relationships within the ophiolite belt which bear on the tectonics of ophiolite genesis, deformation and emplacement, and 3) discuss briefly the tectonics of the ophiolite belt with respect to the regional tectonics of the southwest United States. Detailed structural and petrologic data are presented in Saleeby (in press a, in press b). The paleogeographic implications of the ophiolite belt and adjacent metasedimentary and metavolcanic rocks are discussed in Saleeby and others (in prep.). The geochronological evolution of the ophiolite belt is discussed in Saleeby (in prep. a).

Significant conclusions drawn in this paper are: 1) the Kings-Kaweah ophiolite belt originated at a distant oceanic spreading center where cut by a transverse fracture zone; 2) deformation of the ophiolite was progressive and occurred primarily by fracture zone tectonics while in route to the ancient continental margin; 3) the ancient continental margin was fragmented and tectonically eroded along an extension of the fracture zone; 4) the disrupted ophiolite was juxtaposed against the raw edge of the continent as the continental fragments were displaced; 5) the disrupted ophiolite was accreted to the continental margin as the hanging wall of a subduction zone as a result of a change in plate motions; 6) the tectonically accreted ophiolite belt subsequently served as frontal arc basement during subduction related arc activity; and 7) the suture between oceanic and continental basement terranes remained tectonically active as a longitudinal intra-arc deformation zone during arc activity. This model of ophiolite genesis, deformation, emplacement and subsequent tectonic history is believed to be applicable along the entire length of the Sierra Nevada foothill metamorphic belt (Saleeby, in prep. b).

GENERAL DESCRIPTION OF THE OPHIOLITE BELT AND RELATED ROCKS

The Ophiolite Belt

Plate V is a general geologic map of the Kings-Kaweah ophiolite belt. The gross structure of the belt is that of a huge tectonic megabreccia with a schistose serpentinite matrix. At the north end of the belt clasts range up to 20 km in length, and are referred to as tectonic slabs (after Hsu, 1968) since they contain internal mappable stratigraphic units. The slabs are collectively named the Kings River ophiolite after the Kings River which transects the slab cluster. The slabs are separated by narrow serpentinite melange zones and by cross-cutting plutons of the Sierra Nevada batholith. Southward from the Kings River area the slabs decrease in size to monolithologic blocks. In doing so the ophiolite belt grades into serpentinite matrix melange. The greater part of the melange is named the Kaweah serpentinite melange after the Kaweah River which transects it.

The entire ophiolite belt has been metamorphosed in the albite-epidote to mainly hornblende hornfels facies (after Turner, 1968) by the Cretaceous Sierra Nevada batholith. Metamorphic recrystallization of the ophiolite belt is in many places incomplete. Thus some insight into original mineralogy of the ophiolite protoliths is available. In addition, even where metamorphic recrystallization is complete, earlier textures and structures are commonly well-preserved. Thus protoliths of the metamorphosed ophiolite belt have been readily deduced from field, petrographic, mineralogical and chemical data. Detailed treatment of this data is not the intent of this paper. For sake of brevity the ophiolite will

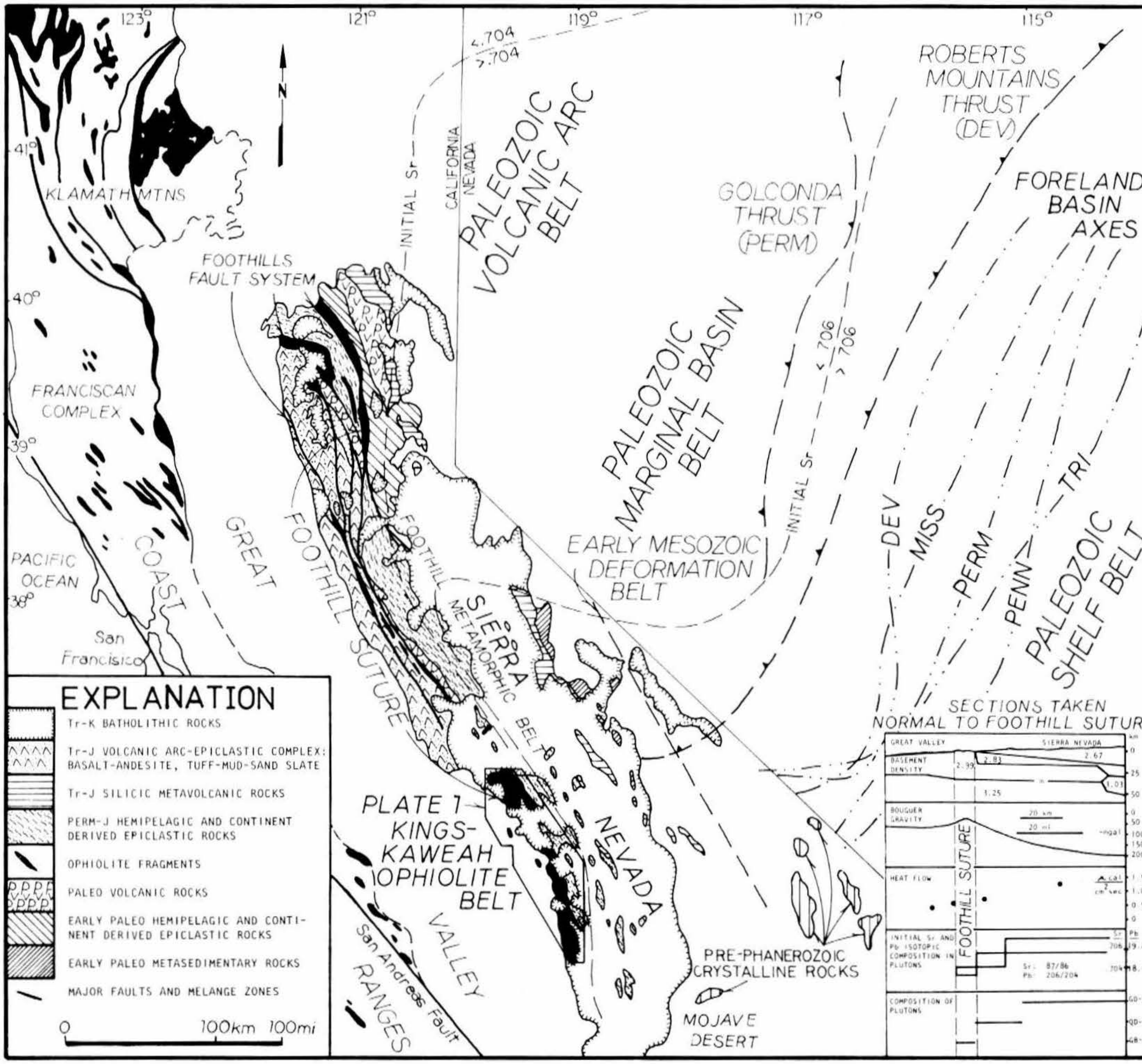


Figure 1. Map showing location of Kings-Kaweah ophiolite belt and significant regional geological features discussed in text. General geology of Sierra Nevada after Clark (1964, 1976), Jennings and Strand (1966), D'Allura and others (1977), Schweickert and others (1977), Saleeby and others (in prep.). Paleozoic regional thrust faults after Burchfiel and Davis (1972), Speed (1977). Paleozoic paleographic belts after Churkin (1974), Stevens (1977). Paleozoic foreland basin axes after Poole and others (1977), Speed (1977), Stevesn (1977). Early Mesozoic deformation belt after Stewart and others (1966), Burchfiel and others (1970), Stevens and Olson (1972), Kelley and Stevens (1975). Initial strontium contours for autocthonous post-Paleozoic igneous rocks after Kistler and Peterman (1973). Major faults and ophiolite fragments of Klamath Mountains and Coast Ranges after Jennings and Strand (1966). Inset at lower right shows plots of several geological parameters taken along a section perpendicular to southern part of foothill suture. Bouquer gravity after Oliver and Robbins (1975); rock density after Cady (1975), Saleeby (1975); heat flow after Lachenbruch (1968); isotopic composition on autocthonous igneous rocks after Kistler and Peterman (1973), Dow and Delevaux (1973), Saleeby (1975), Chen (1977); composition of volumetrically important Mesozoic plutons after Moore (1959), Saleeby (1975), Chen (1977) with gb=gabbro, qd=quartz diorite, gd=granordiorite, qm=quartz monorite.

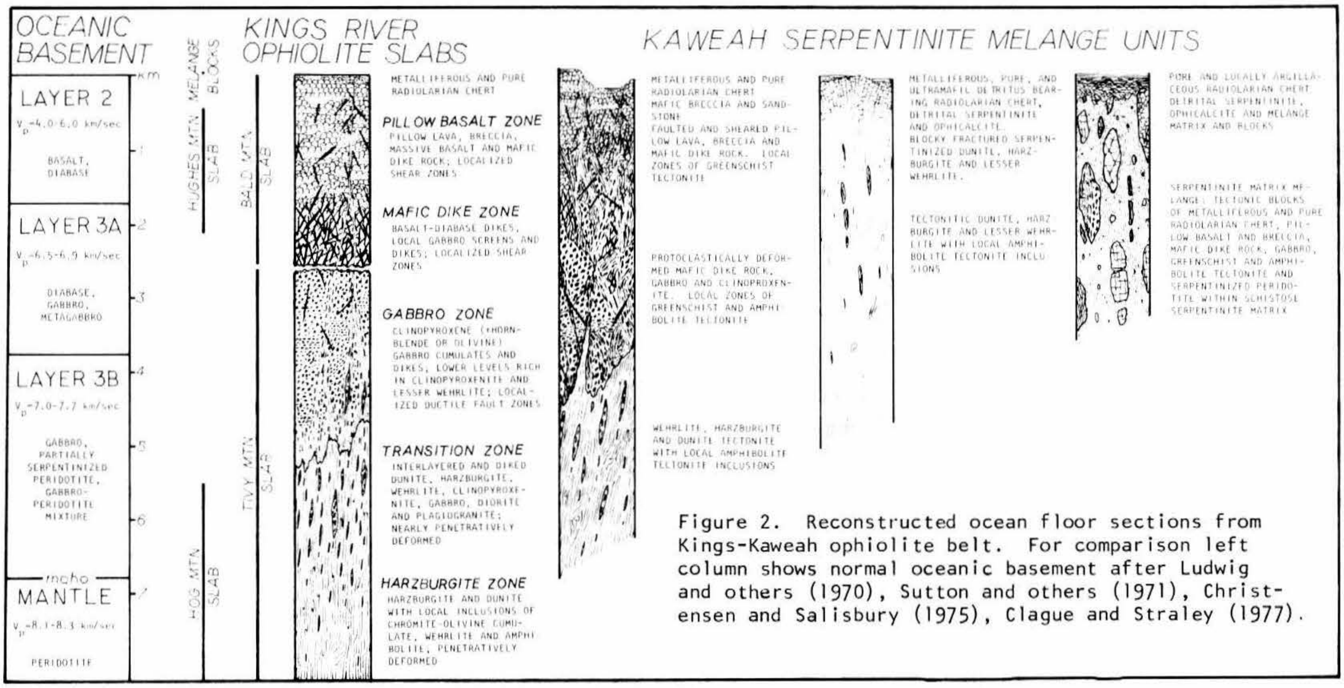


Figure 2. Reconstructed ocean floor sections from Kings-Kaweah ophiolite belt. For comparison left column shows normal oceanic basement after Ludwig and others (1970), Sutton and others (1971), Christensen and Salisbury (1975), Clague and Straley (1977).

be discussed in terms of pre-batholith protoliths. For further information on batholith related metamorphism see Saleeby (1975, 1977, in press a and b, in prep. a).

The Kings River ophiolitic slabs are named after the highest encompassed peak. The slabs are bounded by serpentinite melange zones in most instances. Where not present, the melange zones can be inferred to have existed prior to batholith emplacement. The Hog and Tivy Mountain slabs are predominantly peridotite. These slabs grade into the neighboring melange matrix. Peridotite foliations grade into or are cut by domains of schistose serpentinite. Towards the melange zones the schistose serpentinite domains become dominant until the original peridotite fabric and mineralogy is obliterated producing the melange matrix. Within short distances exotic blocks of gabbro, basalt and chert occur within the serpentinite matrix. The strike of the matrix schistosity is parallel to the long axes of the slabs and to the regional trend of the ophiolite belt.

Within the slabs structures which pre-date melange mixing also occur. Peridotite and gabbro within the Hog Mountain and Tivy Mountain slabs contain a mylonitic foliation. The trend of this foliation is mainly parallel to the trend of the ophiolite belt. However, domains in which foliations have been folded and rotated are common. The folded and rotated domains are truncated by mylonite foliation surfaces which are identical to the folded surfaces. Structural analysis of the mylonites shows that mylonitization proceeded in repeated pulses with early-stage foliation surfaces being truncated, rotated, folded and refolded during succeeding stages of mylonitization. This complex family of foliation surfaces is referred to as S_1. Within S_1 there is a steep plunging lineation (L_1) defined by elongated dimensional markers such as pyroxene porphyroclasts and deformed mafic inclusions. Folding of S_1 and L_1 was predominately about steep plunging axes. Folds in S_1 and L_1 are referred to as F_1. F_1 geometry is variable and complex. Asymmetries suggestive of a dextral sense of motion are not uncommon.

The schistosity of the melange matrix and similar schistositics of the Hog Mountain and Tivy Mountain slabs are referred to collectively as S_2. Along both margins of the Hog Mountain slab, and along the western margin of the Tivy Mountain slab S_1 grades into S_2. This is manifested by a progressive increase of schistose serpentine relative to flattened and streaked out olivine and pyroxene. Along the eastern margin of the Tivy Mountain slab S_2 cuts sharply across S_1. Local zones of both S_2 cutting S_1 and S_1 grading into S_2 occur within the ultramafic slabs. S_1 in northwest orientations grades into S_2, whereas S_1 in other orientations is cut by S_2.

Mafic slabs of Bald Mountain and Hughes Mountain contain a relict shear fabric which is only locally developed in each of them except for the northwest part of the Hughes Mountain slab where it is penetrative. The shear fabric is also steeply dipping and parallel to the regional trend of the ophiolite belt. It is thought to be equivalent primarily to S_1 of the Hog Mountain and Tivy Mountain slabs. Similar shear fabrics in mafic melange blocks appear to be surfaces along which the blocks were rifted apart during melange mixing. Thus the shear fabric may in part also be equivalent to S_2 of the ultramafic slabs and melange zones. As will be discussed later, development of S_1 and S_2 are thought to have partly overlapped in time.

The slabs contain various segments of the original ophiolite stratigraphy. A reconstructed stratigraphic section is shown in Figure 2. Next to the graphic section the intervals spanned by the Kings River slabs are shown. The reconstructed stratal thicknesses are taken from the Tivy Mountain and the Bald Mountain slabs which fit immediately adjacent to one another when the ophiolite is palinspastically restored to its pre-batholith configuration (Fig. 3). The reconstructued ophiolite section consists from the base up of: 1) greater than 4 km harzburgite-dunite with traces of chromitite, wehrlite, clinopyroxenite and gabbro; 2) 2.5 km mafic-ultramafic transition zone composed of the same rocks except wehrlite, clinopyroxenite and gabbro are more significant; 3) 2 km gabbro and lesser clinpyroxenite cumulates; 4) 0.7 km basalt-diabase dike complex which is locally sheeted; 5) 1.8 km basaltic pillow lava and pillow breccia; and 6) greater than 20 m metalliferous radiolarian chert. The reconstructed ophiolite section is interpreted as a sample of oceanic crust and upper mantle. A more detailed discussion of the ophiolite section is presented in Saleeby (in press a).

Southward from the Kings River area the ophiolite fragments decrease in size to form tectonic blocks in serpentinite melange. The large gabbro block at the north end of Smith Mountain is intermediate in size between the Kings River slabs and common melange blocks which range between 1 km and several meters in diameter. Geophysical data (Saleeby, 1975) indicates that the Smith Mountain block continues in the subsurface for at least 7 km north of Smith Mountain. A significant feature of the serpentinite melange is that it consists only of ophiolite assemblage blocks. Blocks of dunite, harzburgite, wehrlite, clinopyroxenite, gabbro, mafic dike rock, pillow basalt,ophicalcite and radiolarian chert are suspended in schistose serpentinite. Ultramafic blocks usually grade outward into the matrix in a fashion similar to that described for the ultramafic slabs of the Kings River area. In contrast, contacts between matrix and mafic and chert melange blocks are usually sharp.

Melange blocks are invariably elongate parallel to the matrix schistosity and the regional trend of the ophiolite belt. Internal structures of the blocks such as mylonite or metamorphic foliation and shear surfaces are usually oriented parallel to the blocks long axes. Chert blocks are usually tabular in shape with bedding also oriented parallel to long axes. Many melange blocks have transverse extension fractures which are occasionally injected with schistose serpentinite. In many instances blocks have been pulled apart along the tension fractures like large boudins. Local kinks in blocks and small-scale folds in the matrix schistosity occur; these are invariably about near vertical axes with many of them having asymmetries indicating a dextral sense of motion.

Outcrop mapping of the melange revealed a clustering of blocks of similar lithology or lithologies. The clusters are shown as melange units on Plate 1. The melange units appear to be the vestiges of once larger blocks or slabs that have been distended into a myriad of smaller blocks by faulting and injection of the more mobile matrix. Within the melange units there are vestiges of primary igneous and sedimentary contacts between different members of the ophiolite assemblage. As discussed below, some primary contacts formed during melange development. The melange units are interpreted as the mixed remnants of ocean floor stratigraphic successions. Stratigraphic successions reconstructed from the units are also shown in Figure 2. The implications of the reconstructions will be discussed below.

Continental Margin Rocks

Depositional remnants of continental margin rocks occur above the Kaweah serpentinite melange. The oldest of these rocks is a chert-argillite olistostrome complex containing olistoliths of shallow water limestone and interbeds of chert and quartzose to subarkosic sandstone. The shallow water limestone blocks contain late Permian fauna believed to be exotic to North America (Saleeby and others, in prep). The chert-argillite complex grades into a volcanic arc-epiclastic sequence. Chert deposition apparently subsided or was overwhelmed as quartzose to sub-arkosic flysch deposition and basalt-andesite volcanism commenced. The continental margin rocks were faulted, folded and flattened along with late-stage deformation of its ophiolitic basement. Deposition of this assemblage appears to have been syntectonic with abundant intraformational reworking. In addition, local uplifts and exposures of ophiolite basement shed ophiolite assemblage olistostromes into the continental margin rocks. Age constraints on the deposition of continental margin rocks place it between the latest Permian and late Jurassic (Saleeby and others, in prep.).

Middle and late Jurassic gabbroic to quartz dioritic plutonic rocks which cut the ophiolite belt appear to be the roots of the volcanic arc rocks (Saleeby, 1975; Saleeby and Sharp, 1977). An important feature of the plutonic rocks is that they were emplaced late in the deformation history of the ophiolite belt following significant tectonic mixing. Thus the plutons cut melange structures and are structurally in tact, but have high temperature deformation features on trend with the structure of the ophiolite belt. The structural relation between the ophiolite belt and the Jurassic plutons is analogous to the structural relation between the depositional remnants of continental margin rocks and the ophiolite belt. The petrogenesis of each was late-stage syntectonic along the pre-existing structural trends of the ophiolite basement. Foliation surfaces of the Jurassic plutons and the continental margin rocks are designated S_3 on Plate V.

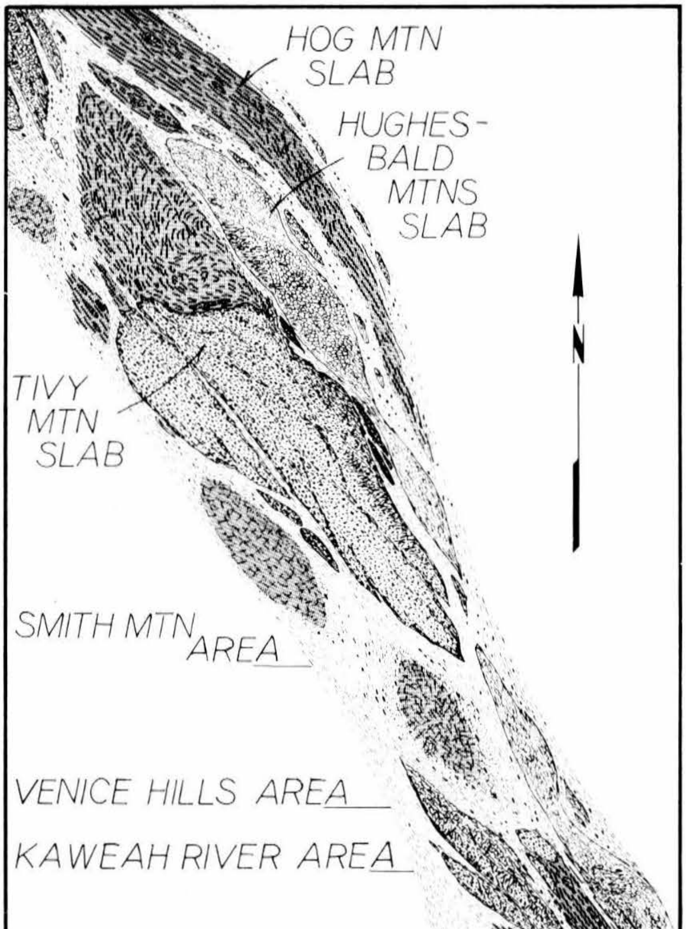
The ophiolite belt is in tectonic contact along its eastern margin with an additional assemblage of continental margin rocks. This assemblage consists of quartzite-argillite olistostromes, quartzose to sub-arkosic massive sandstone and flysch, carbonate turbidites and slide blocks and an upper section of shallow marine and silicic volcanic rocks. It is thought to be equivalent to the upper intervals of the Calaveras Complex exposed further north along the foothill metamorphic belt (Saleeby and Goodin, 1977; Schweickert and others, 1977). Late Triassic to early Jurassic fossils have been recovered from the upper part of this assemblage (Christensen, 1963; Jones and Moore, 1973; Saleeby and others, in prep.). Recent mapping and petrographic work suggests that part of this assemblage is a proximal facies of the epiclastic rocks deposited on top of the ophiolite (Saleeby and others, in prep.).

Geochronology

Geochronological work in conjunction with structural and petrologic work has revealed a prolonged history of igneous and metamorphic events along the ophiolite belt. Gabbro of the Kings River ophiolite transition zone contains rare pods and dikelets of diorite and plagiogranite which appear to be autocthonous magmatic differentiates. Zircon separates from these rocks and similar rocks from three widely spaced gabbro-peridotite blocks from the Kaweah serpentinite melange yield a suite of discordant U/Pb ages whose minimum ages range between 205 m.y. and 270 m.y., and whose upper intercept ages cluster around 300 m.y. Zircon discordance is attributed to Cretaceous thermal metamorphism related to emplacement of the batholith. Intercept ages on young zircon populations are difficult to interpret. The tentative interpretation is that initial crystallization could have ranged back to 300 m.y.; however, it could have occurred as late as about 250 m.y. Since the sparce leucocratic rocks are an integral part of the ophiolite belt's igneous assemblage, their initial crystallization age constraints are taken as ophiolite genesis age constraints.

Regional thermal metamorphism related to the Sierra Nevada batholith is of hornblende hornfels facies. A significant exception is where local zones of albite-epidote hornfels facies rocks occur at significant distances from contacts with batholithic rocks. From these zones mafic metamorphic tectonites of the ophiolite have been dated by K/Ar techniques. The minimum age of these tectonites is 190 m.y. Where similar tectonites have been collected from zones of hornblende hornfels facies rocks the K/Ar system has been completely reset to batholith ages. As discussed below, mesoscopic field relations suggest that the true metamorphic age of these tectonites is the same as the ophiolite genesis age.

The timing of ophiolite deformation is bounded on the upper end by voluminous plutons of the batholith which cut S_1, S_2 and S_3 and lack a tectonic fabric. These plutons have yielded numerous early Cretaceous concordant zircon ages. The intact plutonic rocks which contain S_3 but cut melange structures have yielded concordant middle and late Jurassic zircon ages. Thus tectonic mixing of the ophiolite belt ceased by middle Jurassic time and subsequent deformation of the ophiolite belt and Jurassic plutons ceased by early Cretaceous time. The tectonics of ophiolite genesis, transport, deformation, melange development and emplacement are the subjects of the remainder of this paper.



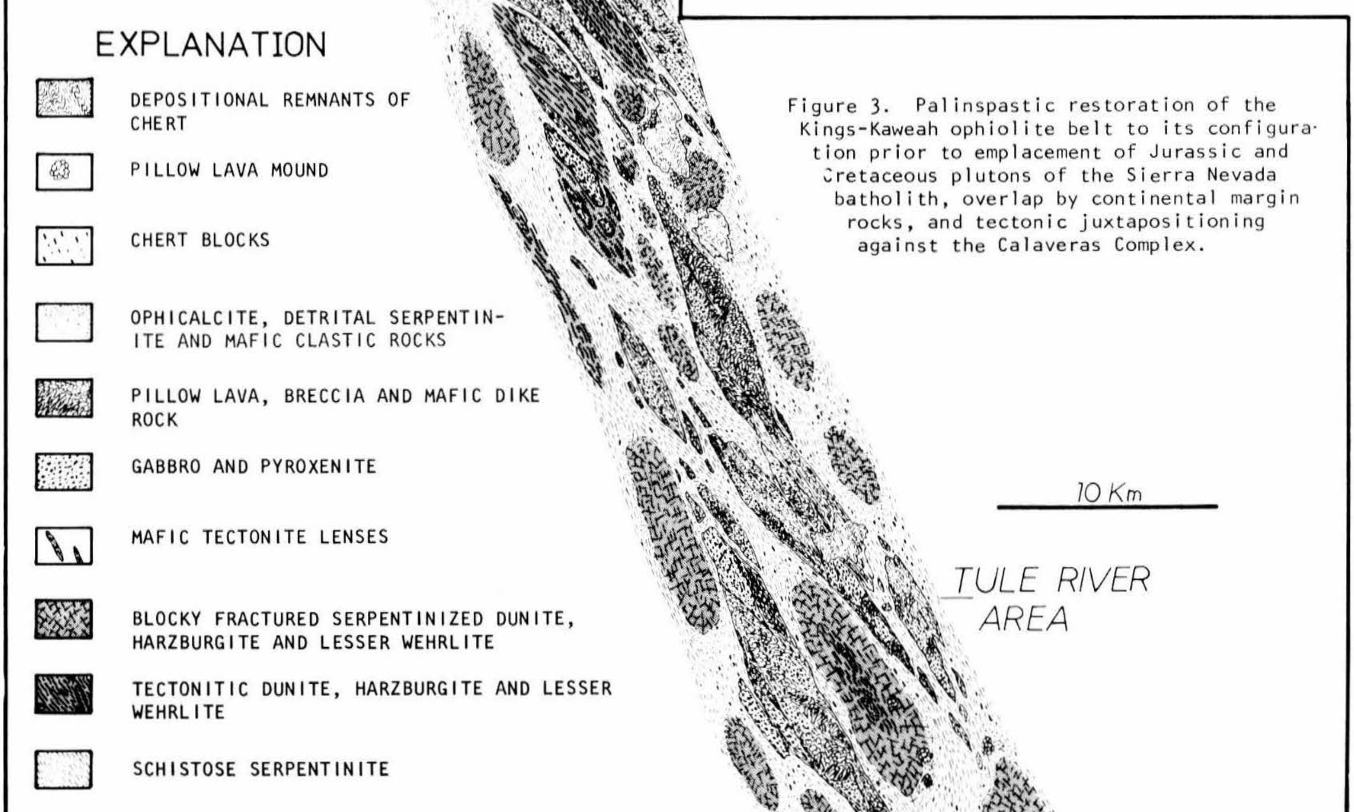
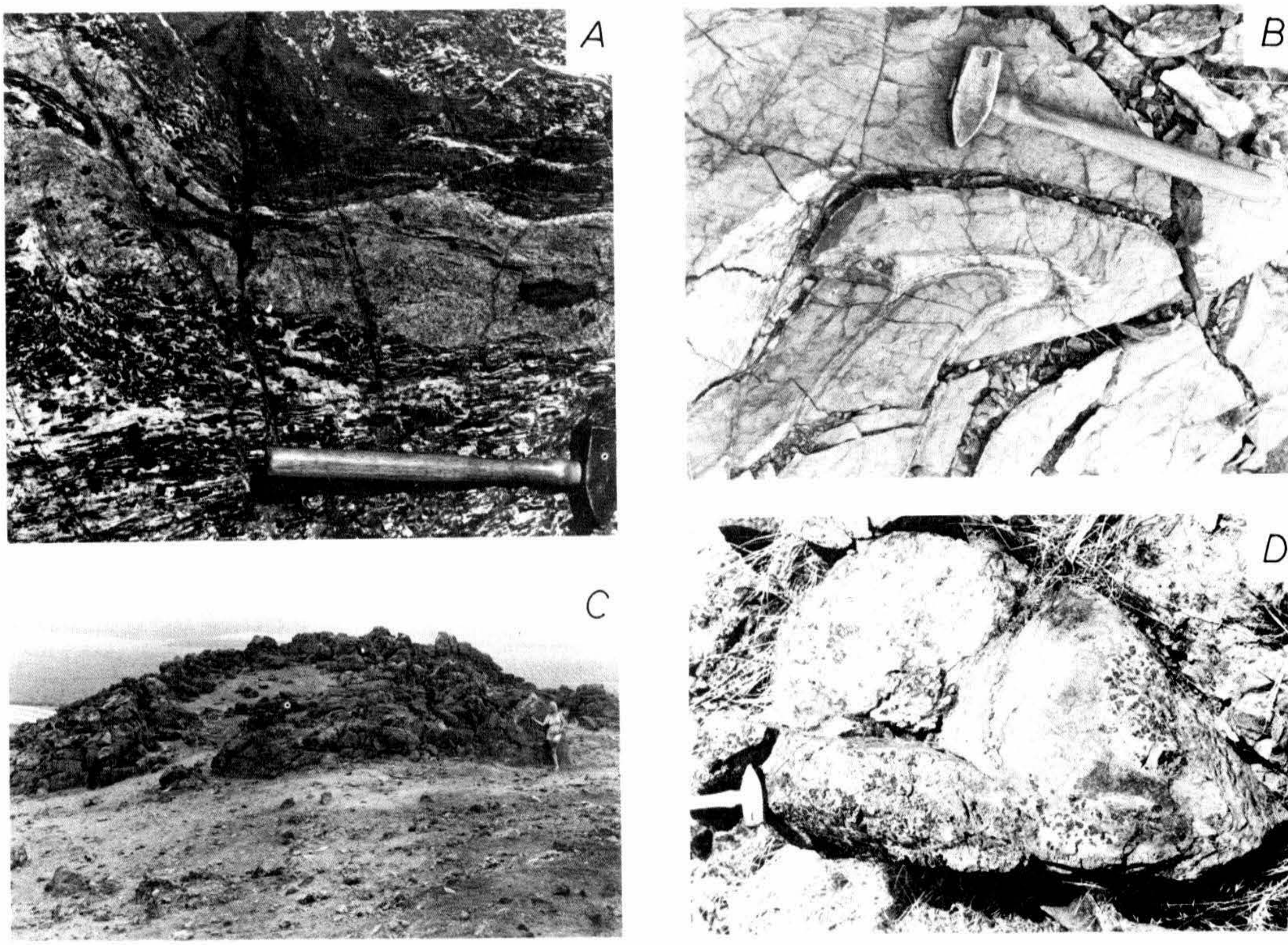


Figure 3. Palinspastic restoration of the Kings-Kaweah ophiolite belt to its configuration prior to emplacement of Jurassic and Cretaceous plutons of the Sierra Nevada batholith, overlap by continental margin rocks, and tectonic juxtapositioning against the Calaveras Complex.



THE FRACTURE ZONE MODEL

A palinspastic restoration of the ophiolite belt to its configuration prior to emplacement of Jurassic to Cretaceous plutons and deposition of the continental margin assemblage is shown in Figure 3. The reconstruction shows the ophiolite belt as a tectonic megabreccia with a penetrative vertical planar fabric. This configuration is significantly different from many other ophiolites which occur as moderately dipping sheets (Moores, 1969; Coleman, 1971; Davies, 1971; Dewey and Bird, 1971; Moores and Vine, 1971; Church, 1972; Gealey, 1977). For this reason an obduction or overthrust model of emplacement is not adopted for the Kings-Kaweah ophiolite belt. A continental margin subduction model of emplacement does not seem applicable either. The tectonic melange of the Kings-Kaweah ophiolite belt is oceanic in origin. Continental margin rocks were deposited across ophiolite melange late in its deformational history subsequent to significant tectonic mixing. In addition, the sedimentary record of the ophiolite belt records transport from the oceanic regime into a continental margin regime which was characterized by non-volcanic hemi-pelagic and terrigenous sedimentation. A volcanic arc was not approached by the sea floor spreading transport of the ophiolite as would be the case in a subduction emplacement model. Finally, metamorphic tectonites of the ophiolite belt are greenschist to amphibolite facies. Blueschist and eclogite facies rocks, which are generally considered characteristic of subduction complexes, are not present along the Kings-Kaweah belt.

An alternative to an obduction or subduction model of ophiolite deformation and emplacement is developed below. Specific structural, petrologic and stratigraphic relations along the ophiolite belt are used in conjunction with recent discoveries in marine tectonics to develop an oceanic fracture zone model. The role of some of the relationships used to develop the model is summarized in Figure 5. Relationships between petrogenesis and deformation of the ophiolite are of primary interest. Critical relationships in igneous, pre-batholith metamorphic, and oceanic sedimentary rocks are covered respectively. Emphasis is placed on the fact that deformation and disruption of the ophiolite was oceanic and progressive, and furthermore, ophiolite genesis was syntectonic. Specific relationships discussed below may have noteworthy alternative interpretations. However, in each instance the fracture zone interpretation appears to be as good or better than alternative interpretations. Furthermore, when all of the relationships are considered together, the fracture zone model seems to be the only model that cannot be dismissed. For sake of brevity the alternative interpretations will not be given equal treatment.

Igneous Deformation

Temporal relationships between the igneous generation of the ophiolite belt and commencement of its deformation history support the fracture zone model. Development of S_1 commenced during the igneous generation of the ophiolite at the oceanic spreading

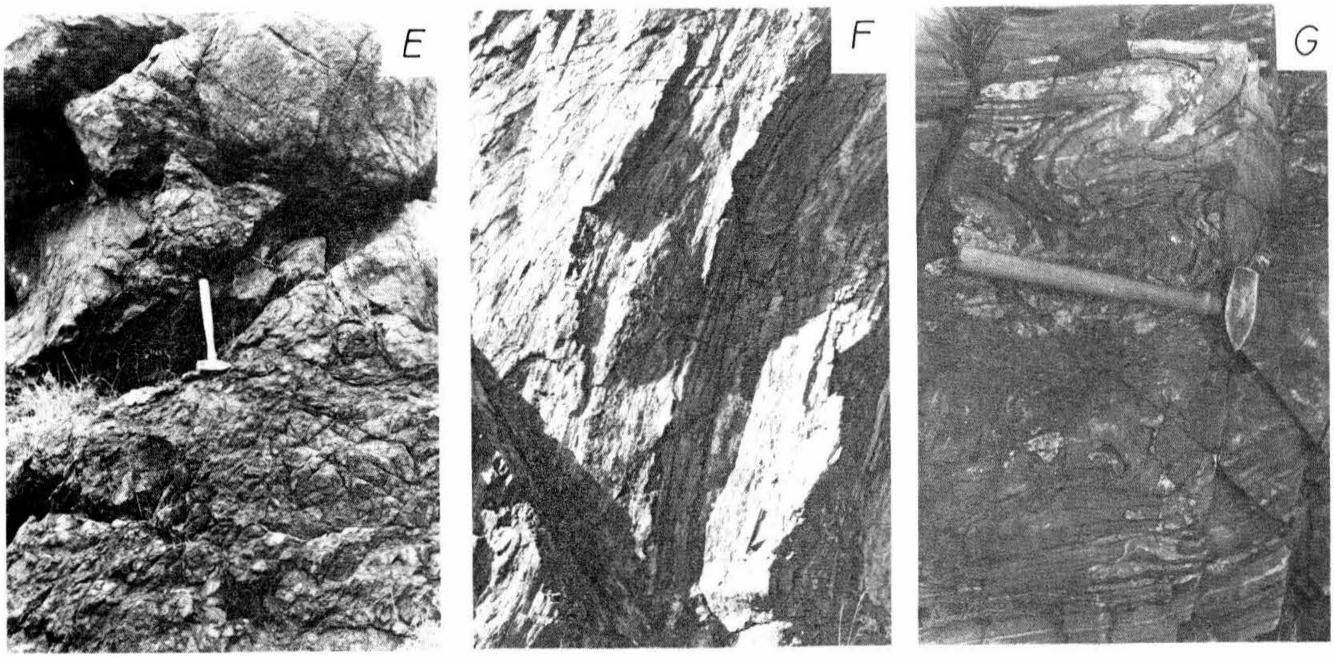


Figure 4. Photographs of some important features along the Kings-Kaweah ophiolite belt. A: Protoclastic deformation in diorite and basalt dikes cutting clinopyroxene gabbro. B: Deformed hydrothermal veins in harzburgite tectonite; veins are flattened into S_1 which is tightly folded around vertical axis with homoaxial open refold. C: Blocky fracturing in serpentinized harzburgite. D: Large clast of ophicalcite composed of smaller ophicalcite clasts (areas rich in dark ultramafic detritus) in micritic matrix; the large clast occurs with other clasts of peridotite and ophicalcite within a micritic matrix. E: Crude bedding in sedimentary serpentinite; upper bed contains up to boulder size clasts, lower bed contains up to cobble size clasts. F: Steep-plunging elongation lineation in harzburgite; L_1 is accentuated by transposed hydrothermal veins. G: Soft sediment folding and brecciation in metalliferous radiolarian chert; dark bands are nearly pure oxide minerals; note how disrupted interval is bounded by intact intervals.

center. Intrusive and extrusive pulses overlapped in time with pulses of mylonitization. Some intrusive masses cut S_1 sharply along part of their length but are in turn cut or transposed into S_1 further along their length. Some merely show chaotic protoclastic-type structures which in most cases converge into S_1 of the surrounding rocks (Fig. 4a).

The position and amount of highly differentiated igneous rocks raises an important point. Pillow lavas of the ophiolite belt are basaltic. Keratophyre and quartz keratophyre are apparently absent. The mafic dike and cumulate gabbro zones of the Kings River ophiolite and equivalent melange blocks lack diorite and plagiogranite. This paucity of highly differentiated rocks contrasts with many other ophiolites which contain significant amounts of intermediate to silicic intrusive and extrusive rocks (Moores, 1969; Dewey and Bird, 1971; Bailey and Blake, 1974; Coleman and Peterman, 1975). Diorite and plagiogranite do occur in trace amounts in the Kings River transition zone and in equivalent melange blocks. It thus appears that the only environment suitable for stagnation and extreme differentiation of magma bodies was in the deeper levels of the ophiolite beneath the main plutonic part of the section. The pockets and dikes of magma which stagnated in the transition zone also concentrated magmatic water during differentiation. This is shown by the presence of primary brown hornblende and by hydrothermal aureoles and veins that formed in the ultramafic host rock. In the hydrothermal zones dunite, harzburgite and wehrlite have been altered to various combinations of serpentine, Cr-chlorite and talc (Fig. 4b). An important feature of these alteration zones is that they also show developmental pulses which overlapped in time with mylonitization pulses in that the zones cut and are cut or transposed by S_1 to various degrees.

Structural analysis of the S_1 tectonites reveals high amounts of flattening and constrictional strain. In addition, persistent pulses of translational movements with folding and rotation about steep axes accompanied the flattening and constrictional strain. It is difficult to envision such complex tectonites forming at a normal oceanic spreading center. However, tectonites similar to those of the Kings-Kaweah ophiolite belt have been recovered from transverse fracture zones (Aumento and others, 1971; Bonatti and others, 1971; Melson and others, 1972; Thompson and Melson, 1972; Bonatti and Honnorez, 1976; Fox and others, 1976). It is proposed that the S_1 tectonites of the Kings-Kaweah ophiolite belt developed along a transverse fracture zone. The S_1 deformation began at the intersection of the fracture zone with the ridge axis and continued for some unknown distance off the ridge axis. Thus, plutonic masses and their contact metamorphic derivatives were protoclastically deformed by S_1 and subsequently folded, rotated and redeformed with development of later-stage S_1. It is important to emphasize that the penetrative tectonite fabric that is present throughout the harzburgite is also present in dunite, wehrlite, pyroxenite, gabbro, diabase, diorite and plagiogranite. A distinctive tectonite-cumulate contact or contact zone, as would be expected with a normal ridge derived ophiolite, does not exist in the Kings-Kaweah ophiolite belt.

Development of S_1 varies with stratigraphic depth in the reconstructed Kings River ophiolite section (Fig. 2). This variation reflects a change in material behavior with depth during S_1 development. The harzburgite and lower transition zones behaved by penetrative ductile and cataclastic flow. Notable exceptions to this are small isolated mafic bodies in the harzburgite zone which syntectonically recrystallized in the amphibolite facies and, intrusive masses in the transition and lower gabbro zones which were protoclastically deformed. The upper transition and lowermost gabbro zones behaved similar to rocks lower in the section except in a less penetrative fashion. Thus local domains in which igneous textures and structures are fairly-well preserved occur within these S_1 tectonites. The tectonites extend through the main part of the gabbro zone as ductile fault zones. In the mafic dike and pillow basalt zones localized shear and brittle fracture zones occur.

The general deformation pattern displayed in the reconstructed Kings River ophiolite section is increasing ductility and pervasiveness with stratal depth. This pattern is believed to be primarily a result of a steep ocean ridge thermal gradient with higher temperatures favoring greater ductility and pervasiveness of deformation. This deformation pattern is believed to have been masked by intense protoclasis at the intersection of the fracture zone axis with the spreading axis. Mafic melange units commonly contain blocks with extremely complex internal structures in which chaotic mixtures of pillow lava, mafic dike rock, gabbro and mafic metamorphic tectonites have contradictory relationships with S_1. The chaotic mafic melange blocks are interpreted as remnants of the intersection zone. The spatial relationships envisioned between the melange units which contain the chaotic mafic blocks and the large slabs which fit into a more conventional ophiolite stratigraphy will be discussed below.

Metamorphic Tectonites

Recent studies of oceanic ridges and fracture zones have shown that these zones are characterized by a distinctive steep vertical metamorphic gradient which passes through zeolite, greenschist and amphibolite facies (Miyashiro and others, 1971; Miyashiro, 1972; Spooner and Fyfe, 1973; Fox and others, 1976). This vertically compressed facies series apparently results from a steep ocean ridge thermal gradient which is related to heat liberated during ocean floor genesis. The effects of a steep ocean ridge thermal gradient are evident in the metamorphic grade of mafic tectonites present along the ophiolite belt (Fig. 2). Data which pertain to this subject comes from within the Tivy Mountain slab and from zones along the serpentinite melange where contact metamorphism by the batholith is at its lowest grade. As stated earlier K/Ar data on the mafic metamorphic tectonites reveals a minimum metamorphic age of 190 m.y. Contact metamorphism by the batholith has severely altered both U/Pb and K/Ar systems of the ophiolite belt, so the true metamorphic age of the tectonites is probably significantly greater. Since protoclastic deformation of diorite-plagiogranite dikes and metamorphic recrystallization of the mafic tectonites are both S_1 features, the true metamorphic age of the tectonites is probably close to the igneous age of the diorite-plagiogranite dikes. Thus metamorphic heat and ophiolite genesis heat are considered the same.

Within the deeper stratal levels of the Tivy Mountain slab gabbroic masses were syntectonically recrystallized to amphibolites during development of S_1. Unfortunately, contact metamorphism by the batholith makes it impossible to resolve the original metamorphic grade of the Tivy Mountain slab's upper levels. The same problem exists with the Bald Mountain and Hughes Mountain slabs which contain the ophiolite's uppermost stratal levels. What can be said is that metamorphic recrystallization was nowhere near as pervasive in the upper levels of the Tivy Mountain slab as in its lower levels, and that ductile, cataclastic and protoclastic flow greatly predominated as deformation modes in its upper levels. Where the protoliths of amphibolite tectonite blocks in serpentinite melange can be deduced, they are usually gabbro. In contrast, low grade amphibolite and greenschist tectonite blocks are most commonly derivatives of mafic hypabyssal and volcanic rock.

The relationships outlined above are interpreted as a result of a steep ocean ridge thermal gradient which controlled metamorphic mineral assemblages developed along the fracture zone where metamorphic recrystallization was the preferred mode of deformation. Pervasive amphibolite facies metamorphism is present between stratal depths of 7 and 11 km in the reconstructed Kings River section. With a temperature range of about 450°C to 650°C for the amphibolite facies (Turner, 1968), this depth-temperature relation corresponds with calculated ocean ridge geotherms (Oxburgh and Turcotte, 1968; Sclater and Franchetean, 1970). The lower grade conditions which existed higher in the section are manifested by localized zones of syntectonic metamorphic recrystallization now preserved only within mafic melange blocks. This localization of metamorphic tectonites at higher stratal levels is thought to be a result of three variables which worked together to produce them: 1) zones of concentrated deformation; 2) a rapidly declining high thermal gradient; and 3) migration of water. As discussed below, the zones of concentrated deformation are thought to have widened with time, and as a result the influx of water into the deforming ocean floor increased with time. However, the rapidly declining thermal gradient put tight time-space constraints on the interval over which metamorphic recrystallization could operate as a significant deformation mode at upper crustal levels.

Progressive serpentinization of the ophiolite belt's ultramafic rocks is thought to have been an important fracture zone process. Serpentinization is known to be an important process along modern oceanic fracture zones (Bonatti and others, 1971; Melson and Thompson, 1971; Bonatti, 1976; Bonatti and Honnarez, 1976). Serpentinization of the Kings-Kaweah belt began with transition zone hydrothermal metamorphism during ophiolite genesis and initial deformation. As stated earlier the hydrothermal zones cut and are cut by or transposed into S_1 to various degrees. The hydrothermal serpentinites do not appear to be directly related to S_2-bearing schistose serpentinites. However, S_2 serpentinization is also thought to have overlapped in time with development of S_1. This is suggested by the gradational relations between S_1 and S_2. S_1 represents the initial deformation and disruption of the newly created ocean floor. As stated earlier S_1 development was progressive. As S_1 developed migration of ocean water into the deforming ocean floors deeper stratal levels was facilitated. As water migrated into the ultramafic rocks syntectonic serpentine growth progressively replaced ductile and cataclastic flow of olivine and pyroxene. Slabs and blocks of S_1-bearing peridotites are the incompletely digested remnants of the young ocean floor's ultramafic zones. It is important to note that steep plunging folds which are so common in the S_1-bearing slabs also occur locally in S_2 of the ultramafic slabs and the melange matrix.

Progressive serpentinization is believed to have led to greater mobility in the young ocean floor. As S_2 domains developed differential tectonic movements were preferentially concentrated along them. This accelerated both tectonic mixing and further serpentinization which led to serpentinite melange formation. As will be discussed below protrusions and surficial debris flows of ultramafic rock appear to have played an integral part in this stage of the ophiolites disruption history.

Syntectonic Petrogenesis

Structural analysis of the ophiolite belt's igneous and pre-batholith metamorphic rocks indicates a syntectonic petrogenesis of the ophiolite belt's crustal segments which can be best explained with a fracture zone model. Progressive deformation along the fracture zone during transport away from the spreading axis led to the formation of ocean floor melange. The fact that the ophiolite belt's melange is oceanic in origin is best displayed in the record of oceanic sedimentation. As with the ophiolite belt's igneous and metamorphic rocks, petrogenesis of its sedimentary rocks was syntectonic. Thus the earliest formed sedimentary rocks are thoroughly mixed into serpentinite melange, with later deposits being mixed to a lesser extent. In the following discussion the oceanic sedimentation history of the ophiolite belt is treated in two sections, clastic and biogenic. It must be emphasized, however, that these sedimentation modes operated simultaneously.

Clastic Sedimentation

Sedimentary breccia and coarse angular sandstone composed of basalt, diabase, gabbro, and rare chert and amphibolite detritus occurs as melange blocks in several localities along the ophiolite belt. Relict bedding is preserved in some blocks. Sedimentary fabrics suggest both talus slope accumulation and debris flow deposition modes. In a couple of blocks deformation makes it impossible to decipher if the breccia is a deformed sedimentary rock or if it originated in a fault zone. Angular clast fault breccias along with rare sedimentary breccias have also been observed in the pillow section of the Bald Mountain slab. Since the sedimentary breccias occur most commonly as melange blocks the deeper stratal levels of the ophiolite were at least locally exposed and eroded prior to melange mixing. Deep level exposures of the ocean floor are only known to occur along fault scarps of transverse fracture zones (Bonatti and others, 1971; Melson and Thompson, 1971; Melson and others, 1972; Thompson and Melson, 1972; Fox and others, 1976; Bonatti and Honnorez, 1976). The mafic sedimentary breccias are interpreted as having been shed from fault scarps formed during the early stages of ophiolite disruption. The breccias were subsequently engulfed into serpentinite melange as the fracture zone evolved to a more chaotic state.

Ultramafic detrital rocks also occur along the ophiolite belt. These consist of detrital serpentinites and ophicalcites. Nearly identical rocks have been recovered from modern fracture zones (Bonatti and others, 1973, 1974). Rarely fine detrital serpentinite will occur as sedimentary matrix for mafic clast breccias, and occasionally basalt and gabbro clasts occur in ophicalcite. The ultrmafic breccias have complex developmental histories which are directly related to deeper level tectonics and also involve abundant surficial reworking.

A significant number of ultramafic melange blocks have structural features which differ significantly from the S_1-S_2 relationships discussed earlier. Superimposed over the peridotite foliation (S_1) is a rounded blocky fracture system with arcuate schistose serpentinite zones woven through the peridotite autoclasts (Fig. 4c). These features grade into several different features. In some instances the schistose serpentinite zones become more pervasive, less accurate and ultimately converge into S_2 of the melange matrix leaving small clasts of serpentinized peridotite dispersed in matrix adjacent to the parent block. In other instances, the serpentinite becomes less or non-schistose with the clasts dispersed through it in a chaotic fashion. In a significant number of instances the ultramafic melange blocks go through similar gradations as mentioned immediately above except calcite and dolomite occur in different amounts through the sequence. First the carbonate occurs interstitial to ultramafic fragments and then it progressively increases in concentration until the ultramafic material is dispersed in a carbonate matrix (Fig. 4d).

The brecciation sequence outlined above is interpreted as having two intimately associated stages. The first stage is autobrecciation as the ultramafic material moved up diapirically into the fracture zone. The second stage is dispersal of the brecciated ultramafic rock as debris flows and turbidities upon surfacing of the ultramafic protrusion. In many instances it is impossible to distinguish between protrusive breccias and sedimentary breccias. Breccias interpreted as definitely protrusive are parts of semi-intact peridotite blocks. Breccias interpreted as definitely sedimentary contain sedimentary structures and clasts or interbeds of chert (Fig. 4e). A similar intimate relationship between protrusion and sedimentary breccias can be observed in ultramafic flows of the California Coast Ranges (Eckel and Myers, 1946; Dickinson, 1966; Cowan and Mansfield, 1970; Lockwood, 1972), and are apparent in modern fracture zones (Bonatti and others, 1974; Bonatti and Honnorez, 1976).

Vertical protrusion of ultramafic rock is known to be an important process along modern fracture zones (Melson and others, 1967, 1972; Thompson and Melson, 1972; Bonatti and Honnorez, 1976; Fox and others, 1976). The steeply plunging elongation lineation (L_1) within S_1 indicates a dominant component of upper mantle - lower crustal vertical flow during and immediately following ophiolite genesis (Fig. 4f). In a fracture zone environment the accent of the hot ultramafic rock would not be confined by lateral spreading about the ridge axis. Thus S_1-L_1 development not only reflects wrench tectonics, but also vertical protrusion tectonics. Protrusion was probably accelerated as water migrated into the deforming ocean floor and serpentinization of the hot ultramafic rock commenced. The blocky fracture pattern discussed above suggests a volume increase during serpentinization. Similar patterns are present around the Burro Mountain ultramafic body of the California Coast Ranges where expansion has been documented (Coleman and Keith, 1971). In addition, serpentinite under high temperature conditions exists in a thermally weakened state (Raleigh and Patterson, 1965). Thus, the upward ductile and cataclastic flow of peridotite is envisioned as having accelerated due to the expansion and weakening of serpentinization. As vertical flow and serpentinization progressed, the protrusive rock continued to weaken, increasing its mobility. The importance of strain history with respect to progressive weakening in these type of bodies has been demonstrated by Cowan and Mansfield (1970). Surfacing of the fracture zone protrusions resulted in monolithologic sedimentary breccias of ultramafic rock.

Talus piles of protruded ultramafic rock are believed to be the main environment of ophicalcite formation. Interaction with percolating ocean water and/or hydrothermal fluids is believed to have been the main cause of ophicalcite formation. A biogenic origin is not considered important here since biogenic limestones are rare along the entire ophiolite belt. A subaerial pedogenic origin (Folk and McBride, 1976) is not considered since radiolarion chert is locally interbedded with and overlies ophicalcite.

The detrital ultramafic rocks show a complex sedimentation history with abundant reworking. Clasts of ophicalcite containing abundant ultramafic detritus occur in later generation ophicalcites and in detrital serpentinites. In addition, interbeds of ophicalcite occur within detrital serpentinite and interbeds of both ophicalcite and detrital serpentinite occur within radiolarian chert. The ophicalcite interbeds appear to have been accumulations of carbonate mud with pebble to sand size ultramafic fragments. In several instances these "diamictites" compose the matrix of chert-clast breccia. As will be discussed in the section on biogenic sedimentation, soft sediment deformation and reworking was an important process along the fracture zone. The protruded accumulations of ultramafic detritus and related ophicalcites were probably disrupted and reworked by further protrusion and wrench tectonics. Local disruption may have also occurred when small mounds of pillow lava were built on the detrital ultramafic rocks.

The detrital ultramafic rocks were readily incorporated into serpentinite melange as both blocks and matrix. In numerous instances the friable detrital serpentinites can be observed in intermediate to advanced stages of disintegration into melange matrix by development of S_2. The fact that the ultramafic clastic sedimentary rocks occur as depositional remnants above melange, as melange blocks and as a local protolith of the melange matrix indicates their syntectonic genesis.

Biogenic Sedimentation

Deposition, soft sediment deformation, lithification and hard rock deformation of radiolarian chert proceeded throughout the disruption history of the ophiolite belt. The earliest formed cherts are mixed as tectonic blocks throughout serpentinite melange, and occur locally within pillow lava slabs and melange blocks. Later-stage cherts rest as highly deformed depositional remnants above detrital ultramafic rocks, late-stage pillow lava mounds and serpentinite melange. Chert melange blocks commonly have stratigraphic thicknesses of about 20 m. Thicknesses between 100 and 200 m occur in the depositional remnants, but these are gross thicknesses due to intense deformation. Since chert deposition was syntectonic a coherent chert section probably never existed. The thicknesses of both the melange blocks and depositional remnants suggest that at least 200 m of chert was deposited on the ophiolite belt prior to deposition of the continental margin assemblage. However, the earlier-formed chert intervals were tectonically mixed into melange prior to and during deposition of the later-formed intervals. Contact metamorphic recrystallization of radiolaria tests prohibits paleontological dating of the cherts.

A significant relationship exists between the composition of the cherts and their structural setting. Cherts occurring as tectonic blocks throughout the melange commonly contain black to dark purple interbeds and disseminations of oxide minerals. These impurities are primarily iron oxide with trace manganese oxide. The metalliferous cherts are notably lacking in argillaceous or volcanic impurities. Cherts occuring as highly deformed depositional remnants above serpentinite melange locally contain thin interbeds and disseminations of argillaceous material. The argillaceous cherts lack significant amounts of oxide minerals, and lack volcanic impurities. Volcanic impurities occur only rarely in cherts that occur with pillow lava. Cherts lacking any significant impurities occur both as dispersed melange blocks, with or without metalliferous chert, and as bedded intervals in depositional remnants which contain the argillaceous cherts.

The relationships presented above are interpreted to be a result of: 1) deposition of radiolarian ooze commencing during ophiolite genesis and continuing throughout ophiolite disruption along the fracture zone; 2) early to middle-stage deposition of basal metalliferous sediments from hydrothermal solutions (Bostrom and Peterson, 1969; Bostrom and others, 1976) emanating from depth at the spreading axis and possibly along the fracture zone for some distance off the spreading axis; 3) later-stage sporadic influx of fine terrigenous material shed from a distant source that was being approached by sea floor spreading transport of the fracture zone complex. Following deposition of the argillaceous cherts the next rocks that appear in the sedimentary record are chert-argillite olistostromes which contain shallow water limestone olistoliths, and interbeds of both continent derived sandstone and argillaceous chert. Thus the ophiolite was approaching a landmass that was not contributing volcanic detritus to the sedimentary record. This important relationship will be discussed further in conjunction with continental margin tectonics.

Stratigraphic settings of the various cherts indicate progressive disruption of the oceanic basement during biogenic sedimentation. The early to middle-stage cherts occur in association with pillow lavas or as dispersed blocks in serpentinite melange. These cherts appear to have had two depositional settings: 1) mafic oceanic basement as shown by their presence in both pillow lava slabs and in pillow lava-bearing melange units; and 2) protruded ultramafic basement as shown by their presence in peridotite melange units where they are associated with ophicalcite and detrital serpentinite. The later-stage cherts were deposited on basement consisting of serpentinite melange. detrital ultramafic rocks and mounds of late-stage pillow lava.

Structural features of the chert assemblage reflect continuous deformational activity along the fracture zone. Structures that are best interpreted as soft sediment in origin occur both in tectonic blocks and in the depositional remnants. These consist of stratigraphic intervals of chert-cemented chert -clast breccias and associated chaotic folds (Fig. 4h). The chaotic intervals are bounded by bedded intervals both of which are commonly cut by hard rock tectonic structures. In several instances chert clast debris flow deposits occur with an ophicalcite matrix. The common occurence of soft sediment breccias and folds is taken as an indicator of an unstable depositional environment. Since the younger cherts overlie serpentinite melange, which contains blocks of older cherts, the instability of the pelagic depositional environment is shown to have been persistent and tectonic in origin.

Early to middle-stage cherts, which occur primarily as melange blocks, were lithified in most cases prior to melange mixing. This is shown by the presence of brittle shear and tension fractures which are the surfaces along which the melange blocks initially broke apart. Ductile deformation features such as pinching and swelling or streaking-out of bedding in many cases cannot be distinguished from soft sediment features. In some instances chert blocks can be shown to have been ductily deformed along with S_2 deformation of the matrix. Thus early to middle stage cherts underwent localized chaotic folding and brecciation prior to lithification, and following lithification they underwent brittle fragmentation to form melange blocks some of which underwent subsequent ductile deformation along with the melange matrix.

Late-stage cherts which occur as depositional remnants above melange are in some ways structurally more complex than the earlier-stage cherts. This relationship is interpreted as a result of deposition and lithification of the earlier cherts occuring on semi-intact basement slabs undergoing localized deformation with deposition of the later cherts occuring on serpentinite melange basement undergoing penetrative deofrmation. Thus, once lithified the earlier cherts were able to escape much of the deformation that the later cherts experienced in a soft sediment to semi-lithified state while sitting on active melange. Chaotic folds and breccias of probable soft sediment origin are locally important in the late-stage cherts. Another important feature of these cherts, which appears to have been inherited from the soft sediment to semi-lithified state, is the presence of large massive domains with local clasts and rootless folds. The massive domains grade into or sharply abut against bedded domains. The massive domains are interpreted as ponds of reworked radiolaria ooze which slid across and ripped up beds of compacted ooze. In addition some chert beds are graded with respect to radiolaria test size which suggests reworking of radiolaria ooze by turbidity current mechanisms. Both bedded and chaotic domains of the depositional remnants are commonly cut by a spaced cleavage which locally grades into a penetrative cleavage. Where bedding is preserved the cleavage is occasionally axial planar to steep-plunging folds. In several instances the cleavage cuts across limbs of chaotic soft sediment folds. The cleavage is coplanar to S_2 of the underlying melange matrix. The outcrop pattern of the depositional remnants is highly suggestive of an infold relationship with the underlying melange (Plate V).

It must be emphasized that a distinct line cannot be drawn between early, middle and late-stage cherts. Early and late-stage cherts can be distinguished by the structure-composition relations outlined above. Middle-stage cherts appear to represent a gradition both in structure and composition between early and late-stage cherts. The fact that soft sediment and progressive hard rock deformation occur throughout the chert assemblage coupled with the compositional variation outlined above indicates that the ocean floor was progressively disrupted in an oceanic environment en-route to the continental environment. A survey of present day marine tectonic environments reveals that a large fracture zone will serve as the only suitable analogue.

Fracture Zone Tectonics and the Structure of Oceanic Crust

The syntectonic history of igneous, metamorphic and sedimentary petrogenesis displayed in the Kings-Kaweah ophiolite belt is diagramatically summarized using a fracture zone model in Figure 5. Mafic magma and harzburgite residue are shown ascending beneath the ridge axis in accord with sea floor spreading theory (Green and Ringwood, 1967; Kay and others, 1970; Green, 1970, 1971; Dewey and Bird, 1971). The model shows anomalous oceanic crust being created at the intersection of the spreading center and the axis of the fracture zone. The anomalous crust is shown as having two main components. 1) Mafic pillow lava, hypabyssal and deeper plutonic rock characterized by chaotic protoclastic deformation and mixing. These rocks now exist as complex melange blocks and melange units. 2) Ultramafic protrusions which ascended into the fracture zone from the mantle while hot, and which upon reaching crustal levels underwent serpentinization and subsequently surfaced, shedding ultramafic detritus. The large proportion of ultramafic rock along the ophiolite belt, the common occurence of peridotite-chert melange units, and the monolithologic nature of most detrital ultramafic rocks indicate that a significant amount of anomalous oceanic crust was created by ultramafic protrusion. It follows that a significant amount of spreading probably occurred along the axis of the fracture zone due to protrusion tectonics. This has been suggested for large modern fracture zones (Van Andel and others, 1969; Thompson and Melson, 1972; Bonatti and Honnorez, 1976). In addition, protrusion tectonics probably played a significant role in serpentinite melange formation. The anomalous oceanic crust was generated in a semi-tectonically mixed state with chaotically deformed mafic crustal blocks interwoven with ultramafic protrusions and their sedimentary derivatives. This configuration was subjected to prolonged wrench tectonics which resulted in serpentinite melange. The oceanic sedimentation record above the serpentinite melange indicates that the melange too represents anomalous oceanic crust. It is suggested that serpentinite melange is a significant anomalous crustal component in present-day fracture zones with large ridge offsets.

The model also shows a more conventional-type of oceanic crust exposed by faulting along the margin of the fracture zone. This is presently represented by the Kings River ophiolite which has the remnants of normal ocean floor stratigraphy (Fig. 2). The relationship portrayed above is best displayed today along the Vema Fracture Zone of the equatorial Atlantic where normal oceanic crust is apparently exposed along the fracture zone's northern wall while disrupted and protruded crust is exposed along its axes and southern wall (Bonatti and Honnorez, 1976).

The effects of fracture zone tectonics (protrusive and wrench) are evident in the Kings River ophiolite; however, its stratal succession indicates that normal ridge crustal generation processes were permitted to operate. This pattern is intuitively pleasing since anomalous fracture zone crust must at some interval grade laterally into normal ridge created crust. The Kings River ophiolite is interpreted as having originated in such a gradation interval.

The complexity of the ophiolite belts S_1 tectonites can be conceived of as a result of both wrench and protrusion tectonics. As the hot upper mantle and lower crust ascended into the fracture zone it was polydeformed. The deformations consist of: 1) vertical extension by upward flow; 2) flattening in the plane of the fracture zone by forcing its crustal levels apart during protrusion; 3) shear and translation in the plane of the fracture zone by wrench faulting; 4) rotation and folding about steep axes in the plane of the fracture zone due to wrench movements; and 5) a probable complex system of dip-slip faults, antithetic strike-slip faults and shallow plunging folds that are ubiquitous in continental wrench zones (Moody and Hill, 1956; Lillie, 1964; Reed, 1964; Dickinson, 1966; Harding, 1973, 1974; Wilcox and others, 1973; Sylvester and Smith, 1976).

The fact that fracture zone deformation of the ophiolite belt was progressive is well-displayed by the contradictory cross-cutting relations between steep to shallow plunging folds, different stage S_1 surfaces, and different stage igneous pulses. The inclusion of chert blocks in serpentinite melange and the deposition of later-stage cherts across the melange with their subsequent deformation demonstrates the longevity of progressive deformation. As outlined in the next section, this deformation continuum is believed to have extended from the oceanic realm into the ancient continental margin as the ophiolite belt was transported and emplaced into its present position.

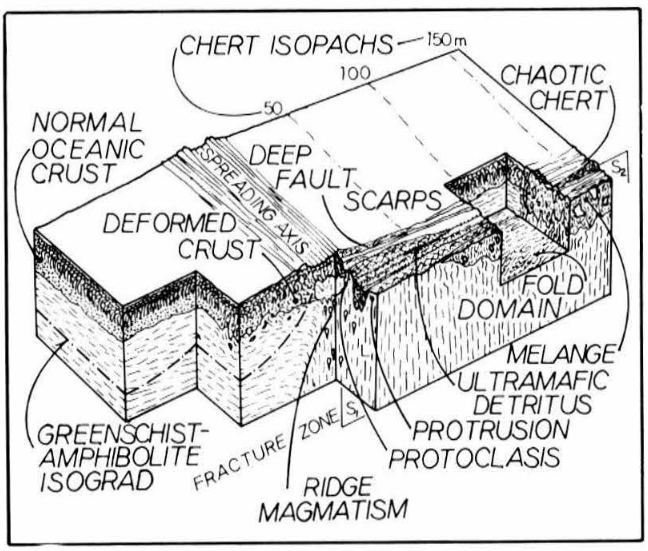


Figure 5. Schematic block diagram showing how critical features of the Kings-Kaweah ophiolite belt fit into an oceanic fracture zone tectonic model. Regional relationships suggest a north-south trend for the fracture zone making this view of the block diagram towards the northwest.

THE ANCIENT CONTINENTAL MARGIN

The fracture zone model for the origin, deformation and sea-floor spreading transport of the Kings-Kaweah ophiolite belt has been developed above using data solely from the ophiolite belt itself. The fracture zone history of the ophiolite belt apparently began in the latest Paleozoic and probably extended into the Triassic. Recent workers have cited regional structural and stratigraphic evidence for early Mesozoic tectonic truncation and transcurrent faulting of the ancient southwest continental margin (Hamilton and Myers, 1966; Jones and others, 1972; Jones and Moore, 1973; Burchfiel and Davis, 1972; Silver and Anderson, 1974; Schweickert, 1976). This tectonic regime is believed to have been directly related to fracture zone tectonics as discussed above. Thus the fracture zone is believed to have extended from well within the oceanic realm into the ancient continental margin. Outstanding modern examples of complex wrench systems which involve both oceanic and continental domains include the Macquarie Ridge-Alpine Fault system of the southwest Pacific (Griffiths, 1971; Griffiths and Varne, 1972), the San Andreas-Queen Charlotte system which rims western North America (Wilson, 1965) and the Spitsbergen Fracture zone of the Arctic Ocean (Lowell, 1972). Considering the complex histories of these sytems one is forced to conclude that significant complexities that could have involved triple junctions and microplates are probably irresolvable in the ancient system. With this in mind, a simplistic tectonic model is outlined below for the continental margin deformation and emplacement of the Kings-Kaweah ophiolite belt. A fuller treatment of this model is given in Saleeby and others (in prep.) and Saleeby (in prep. b).

Foothill Suture

The Sierra Nevada foothill metamorphic belt coincides with a tectonic suture in the earth's crust (Fig. 1). Suture is used here to mean a zone of joining. As discussed below the foothill suture joins fossil late Paleozoic to early Mesozoic oceanic lithosphere to older continental lithosphere. In the south the suture is defined by the Kings-Kaweah ophiolite belt. In the north it is defined by the foothill fault system (Clark, 1960; Schweickert and others, 1977). The significance of the foothill suture is shown by several points: 1) all Sierra Nevada ophiolite remnants occur along it; 2) highly deformed and tectonically mixed rocks which occur along it (Clark, 1960, 1964; Morgan, 1973; Duffield and Sharp, 1975; Ehrenberg, 1975; Behrman, 1978; Saleeby, in press a, b) indicate that it was a zone of major translation; 3) the distinct changes in the gross structure of the crust and upper mantle which coincide with the suture (Fig. 1, inset) can be best explained as a result of a fossil contact between oceanic and continental lithosphere; 4) Jurassic and Cretaceous batholithic rocks emplaced into and to the east of the suture have systematic petrochemical variations (Fig. 1, inset) which can be best explained as a result of the batholith having been emplaced across a contact between oceanic and continental lithosphere; and 5) as discussed below highly contrasting lithologic and structural terranes are juxtaposed along it (Fig. 1).

The suture in the south is exposed as a penetratively deformed ophiolite terrane, whereas in the north it's exposed as a fault system in primarily younger epiclastic and arc volcanic rocks. This is believed to be a result of deeper levels of exposure occurring towards the southern end of the metamorphic belt as discussed earlier. Many of the penetrative deformational features present in the metamorphic belts ophiolitic basement rocks pre-date overlap by the younger epiclastic and arc volcanic rocks. Deformational features in the younger rocks and the foothill fault system are the last expressions of deformation along the suture. It is significant that these late-stage deformations followed the older trends established in the ophiolitic basement rocks.

The foothill suture represents the locus of significant tectonic juxtapositioning. Late Paleozoic ophiolite remnants and overlying early Mesozoic epiclastic and arc volcanic rocks are juxtaposed against a complex of Paleozoic to early Mesozoic continental margin rocks which lie east of the suture. These rocks appear to be remnants of the fragmented continental margin. This fragmentation is believed to be linked to fracture zone tectonics of the Kings-Kaweah ophiolite belt, and to emplacement of the ophiolite belt against the continent's edge.

Continental Margin Fragmentation

Paleozoic rocks east of the Sierra Nevada constitute the southern end of a system of paleogeographic belts that can be traced as far north as central Alaska (Churkin, 1974). The paleogeographic belts consist of volcanic arc, marginal basin and shelf terranes (Fig. 1). Through eastern California and Nevada the paleogeographic belts have northeast trends which are exemplified by facies patterns and Paleozoic thrust belts (Fig. 1). The shelf rocks appear to overlie pre-Phanerozoic crystalline basement, whereas marginal basin and volcanic arc rocks were apparently deposited on transitional or oceanic basement.

Remnants of the Paleozoic belts are present in roof pendants of the eastern Sierra Nevada and possibly in the Shoo Fly complex of the northern Sierra Nevada (Speed and Kistler, 1977; J.N. Moore, personal communication, 1977). These exposures mark the western limit of the Paleozoic belts, and thus a zone of pre-batholith tectonic truncation must have passed longitudinally through the Sierra Nevada. Tectonic truncation of the Paleozoic belts is believed to have been a direct result of wrench movements along the foothill suture. The foothill suture is envisaged as a segment of a transform plate juncture which extended from the fracture zone and cut obliquely across the ancient continental margin. Fragments of the Paleozoic belts were displaced by oceanic lithosphere during truncation.

Truncation of the Paleozoic belts resulted in a major change in the structural grain of the southwest continental margin. Northeast structural and stratigraphic trends, which prevailed throughout the Paleozoic, were terminated and replaced by Mesozoic northwest trends (Fig. 1). The northwest trends have persisted through the Cenozoic and are now manifested by the San Andreas fault system.

This change in structural grain is evident within Paleozoic strata adjacent to the truncation zone. In Paleozoic strata exposed immediately east of the Sierra Nevada northwest trending fold axes, cleavages, thrust faults and strike-slip faults of Mesozoic age are superposed over earlier northeast trending structures (Stewart and others, 1966; Burchfiel and others, 1970; Stevens and Olson, 1972; Kelley and Stevens, 1975; Sylvester and Babcock, 1975; Dunne and Gulliver, 1976; J.N. Moore, personal communication, 1977; Saleeby, unpub. data). A similar pattern of superposed structures exists in Paleozoic rocks present in roof pendants of the eastern Sierra Nevada (Kistler, 1966; Brook, 1977; Russel and Nokelberg, 1977). It must be emphasized that the northwest trending structures of the Sierra Nevada do not represent a single deformational event. Instead, deformation along northwest trends occurred continuously, or in numerous pulses, throughout the Mesozoic (Nokelberg and Kistler, 1977; Saleeby, in prep. b).

Roof pendants east of the Kings-Kaweah ophiolite belt record the history of early Mesozoic sedimentation and tectonics along the fragmented edge. These rocks are treated in-depth in Saleeby and others (in prep.). As discussed earlier they consist of continent derived massive sandstone, flysch, olistostromes and an upper section of shallow marine and silicic volcanic rocks. This assemblage was probably deposited on continental crust as shown by isotopic studies on their enclosing batholithic rocks (Kistler and Peterman, 1973, 1975; Doe and Delevaux, 1973; Chen, 1977). However, this assemblage may not be in its original position relative to similar age rocks resting above Paleozoic strata immediately east of the Sierra Nevada (Jones and Moore, 1973; Saleeby and others, in prep). The clastic rocks were reworked from the truncated Paleozoic shelf belt. They were apparently shed as submarine aprons and fans across fragmented continental basement. The basement was probably undergoing longitudinal wrench movements along the new Mesozoic trends during clastic sedimentation. This tectonically active depositional environment is believed to have given rise to the chaotic deposits of this assemblage.

Structural data on Paleozoic and Mesozoic continental margin rocks east of the Kings-Kaweah ophiolite belt suggest that a longitudinal dextral wrench system worked in conjunction with transverse shortening during the early Mesozoic (Saleeby, in prep. b). This pattern is also evident along the Kings-Kaweah ophiolite belt. These structural patterns suggest that the fracture zone complex was transported from the south, and that the continental margin fragments were displaced northward.

Plate tectonic transport of the ophiolite belt and the displaced continental fragments to the north is also implied by regional considerations. 1) Lower Paleozoic rocks of southeastern Alaska constitute part of an anomalous continental fragment which may have been transported by right-slip faulting from the California region (Mongar and Ross, 1971; Jones and others, 1972). 2) Another anomalous terrane of Triassic age, which extends from south-central Alaska through British Columbia, has yielded equatorial paleolatitudes (Jones and others, in press). 3) Plate tectonic reconstructions of the Mesozoic western Pacific yield mainly east-west trending spreading axes with large north-south trending fracture zones (Larson and Chase, 1972; Hilde and others, 1977). In addition, there is known to have been 4,500 km of northward drift of the Pacific ocean floor since the middle Mesozoic (Larson and Chase, 1972). The time intervals for which these plate tectonic relations are applicable post-date the fracture zone history of the ophiolite belt. However, the consistency between these relations, and the structural configuration of the ophiolite belt and the ancient continental margin suggest that all of these tectonic processes are related to the same kinematic regime.

Continental margin rocks lying above the ophiolite belt record its transport history into proximity of North America. The chert-argillite olistostrome complex was acquired at some unknown distance from the continental margin during transport from the South Pacific (Saleeby and others, in prep.). Large submarine sliding covering thousands of square kilometers of ocean floor is a significant modern process adjacent to both stable and mobile continental margins (T.C. Moore and others, 1970; Embley, 1976; D.G. Moore and others, 1976). The source for the ancient olistostrome complex is unknown. The exotic nature of the fauna within limestone olistoliths indicates that the source was not the North American continent. The olistostrome complex and its exotic fauna may have been derived from outboard borderland and/or orogenic terranes which rimmed the western and southern margins of North America in the latest Paleozoic (Saleeby and others, in prep.).

It is significant that the chert-argillite olistostrome complex grades into distal quartoze to subarkosic flysch. Furthermore, this flysch sequence appears to be the distal equivalent of clastic rocks shed directly off the fragmented North American Paleozoic shelf. The extremities of a large submarine fan system derived from the fragmented shelf are envisaged as lapping across the cite of final chert-argillite deposition. The possible spatial and temporal complexities of this relationship are discussed in Saleeby and others (in prep.).

Shortly after clastic sedimentation began subduction tectonics commenced along the Mesozoic trends. This is shown by the remnants of the arc rocks along the ophiolite belt and the early Mesozoic silicic volcanic rocks east of the ophiolite belt. Regional age data on volcanic and plutonic rocks suggest that this transition occurred during the Triassic (Evernden and Kistler, 1970; Crowder and others, 1973; Schweickert, 1976b; Morgan and Stern, 1977; Saleeby and others, in prep.; P.C. Bateman and O.T. Tobisch, oral communication, 1977).

<u>Subduction and Ophiolite Emplacement</u>

Transcurrent (wrench) faulting has recently been cited as an important mechanism for ophiolite emplacement along continental margins (Dewey and Karson, 1976; Brookfield, 1977). In this view initial juxtaposition of oceanic lithosphere against continental lithosphere occurs by wrench faulting, and actual ophiolite emplacement occurs during a change in plate motions which results in a convergent component between the juxtaposed plates. A similar mechanism is envisaged for the Kings-Kaweah ophiolite belt (Fig. 6). It is not unreasonable to assume that the ancient fracture zone complex was tens of kilometers wide during the later stages of its evolution - considering the width of modern fracture zones with large offsets (Thompson and Melson, 1972; Sclater and Fisher, 1974; Bonatti and Honnorez, 1976). A widely accepted corollary to plate tectonic theory is that continental lithosphere cannot be subducted beneath oceanic lithosphere due to their relative densities (McKenzie, 1969). Similar logic is used in deciphering the fate of the fracture zone complex during the onset of subduction. Taking into account that much of the fracture zone complex was serpentinite, and that serpentinite is significantly less dense than continental crust, the consuming break is believed to have formed on the oceanic side of the fracture zone complex. Thus the change in plate motions accreted the fracture zone complex to the "raw edge" of the continental margin. As the transform juncture evolved into an oblique subducting juncture the fracture zone complex was stranded as the subduction zone's hanging wall. Evolution of large fracture zones into subduction zones during changes in plate motions has been postulated for several present day Pacific subduction zones (Uyeda and Miyashiro, 1974; Falvey, 1975; Hilde and others, 1977). At least one of these instances (Tonga-Kermedac) has yielded ophiolite assemblage dredge hauls from its inner-trench walls (Fisher and Engel, 1969).

Following the change in plate motions the accreted fracture zone complex served as frontal arc basement. However, the arc rocks and their ophiolitic basement are not considered to have been in their final position along the foothill suture until the end of the Jurassic when tectonic deformation along the ophiolite belt ceased.

As stated earlier, the arc plutonic and volcanic rocks of the Kings-Kaweah region were syntectonically generated. Studies in the foothill metamorphic belt further north and in roof pendants to the east reveal similar relations (Parkison, 1976; Nokelberg and Kistler, 1977; Behrman, 1978; Saleeby, in prep. b; Saleeby and others, in prep.). In the Kings-Kaweah region the arc plutons were protoclastically deformed while the volcanic sequence was faulted and in some instances penetratively deformed. There were also uplifts and exposures of ophiolite basement which shed olistostromes into the arc sequence. The structural trends of the arc deformation followed pre-existing trends in the ophiolitic basement. It must be emphasized that Triassic and Jurassic arc rocks throughout California represent only small fragments of the original arc terrane. The original position of these fragments relative to one another may not be easily resolved.

Longitudinal wrench disruption and dispersion of active arc and inner trench wall terranes is known to be an important process along the modern circum-Pacific in zones of oblique convergence (Allen, 1962, 1965; Allen and others, 1970; Wilson, 1965; Fitch, 1972; Karig, 1974; Karig and others, 1975, 1977; Brookfield, 1977; Curray and others, in press). A significant northward component in Mesozoic oblique subduction is believed to have been dissipated by intra-arc wrench movements along the foothill suture and within the fragmented edge of the continent. Transverse shortening worked in conjunction with longitudinal wrench movements. This transpressive (after Harland, 1971) tectonic regime is believed to have been facilitated by the pre-weakened state of the arc basement which consisted of the fragmented continental edge and the tectonically accreted fracture zone complex.

CONCLUSIONS

The Kings-Kaweah ophiolite belt was generated during the latest Paleozoic at a distant east-west trending oceanic spreading center where cut by a major north-northwest trending transverse fracture zone. The fracture zone extended from the oceanic realm into the ancient southwest continental margin where it truncated earlier northeast trending structures and facies patterns.

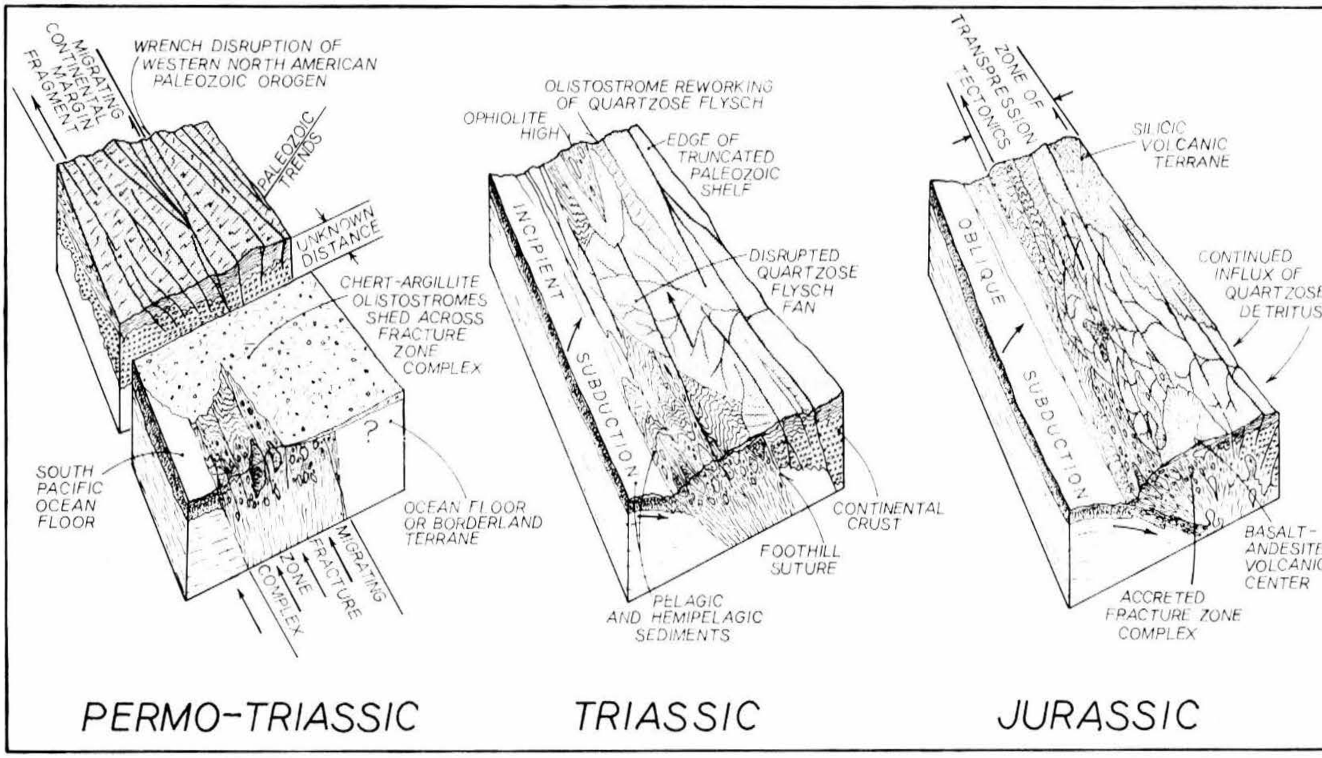


Figure 6. Series of block diagrams which show continental margin emplacement history of Kings-Kaweah ophiolite belt. View is northward along the foothill suture.

Along the axis of the fracture zone anomalous oceanic crust was created. This consisted of protoclastically deformed mafic igneous rock and protruded ultramafic rock. Away from the axial region of the fracture zone normal oceanic crust was created. Remnants of the normal crust also show the effects of fracture zone deformation however. Metamorphic-tectonites of greenschist and amphibolite facies were created during fracture zone tectonics. The heat which drove the metamorphic reactions was the ambient heat of ophiolite genesis. Protrusion and wrench tectonics worked together to progressively disrupt the newly created ocean floor. Progressive disruption and serpentinization led to the development of serpentinite-matrix melange.

Oceanic sedimentation proceeded throughout the genesis and disruption history of the ophiolite belt. Mafic and ultramafic detrital rocks were shed off of upfaulted and protrusive highs. Radiolarian chert was also deposited during genesis and disruption. The earlier formed oceanic sedimentary rocks were thoroughly mixed into serpentinite melange. Later deposits were mixed to a lesser extent. Several of the latest deposits remain as highly deformed depositional remnants above melange. The latest formed cherts have local interbeds of argillaceous material which record encroachment of the fracture zone complex into the continental margin environment.

As the ophiolite belt was transported northward along the fracture zone into proximity of the continental margin fragments of the continental margin were displaced by wrench movements. Chert-argillite olistostromes with blocks of shallow water late Permian limestone containing exotic fauna were shed across the fracture zone complex enroute to the continental margin. By this time the ophiolite belt had already been chaotically mixed by fracture zone processes. As the ophiolite belt moved into closer proximity of the truncated margin terrigenous sedimentation overwhelmed hemi-pelagic sedimentation.

During the Triassic a significant convergent component had developed along the fracture zone. Disrupted ocean floor of the fracture zone was accreted to the truncated edge of the continent as the hanging wall of an oblique subduction zone. A magmatic arc developed along the fragmented edge of the continent in response to subduction. The arc lapped across the suture between the accreted fracture zone complex and the truncated edge of the continent. As the arc evolved it was deformed and disrupted by both transverse shortening and continued wrench movements. Arc deformation was facilitated by basement mobility. The basement consisted of a wide zone of fragmented ocean floor and continental margin rocks.

The tectonic regime outlined above led directly to the Franciscan regime and the related emplacement of the major part of the Sierra Nevada batholith. The Cretaceous batholith further disrupted and metamorphosed the Kings-Kaweah ophiolite belt leaving it as a healed tectonic suture in the earth's crust.

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